Laser Measurements for High-Pressure Combustion: Challenges and Opportunities

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- Graduate students: Mathew Thariyan, Ning Chai, Daniel Richardson, Aizaz Bhuiyan
- Research staff: Scott Meyer, Yu Matsutomi, Sameer Naik
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Outline of the Presentation

- Optically Accessible Gas Turbine Combustor Facilities
- Dual-Pump CARS Measurements: Challenges and Optical System
- Femtosecond CARS for Single-Shot Temperature at 5-10 kHz Data Rates
- Laser System for 5-10 kHz PLIF and PIV, 5 kHz OH PLIF Measurements
- Conclusions

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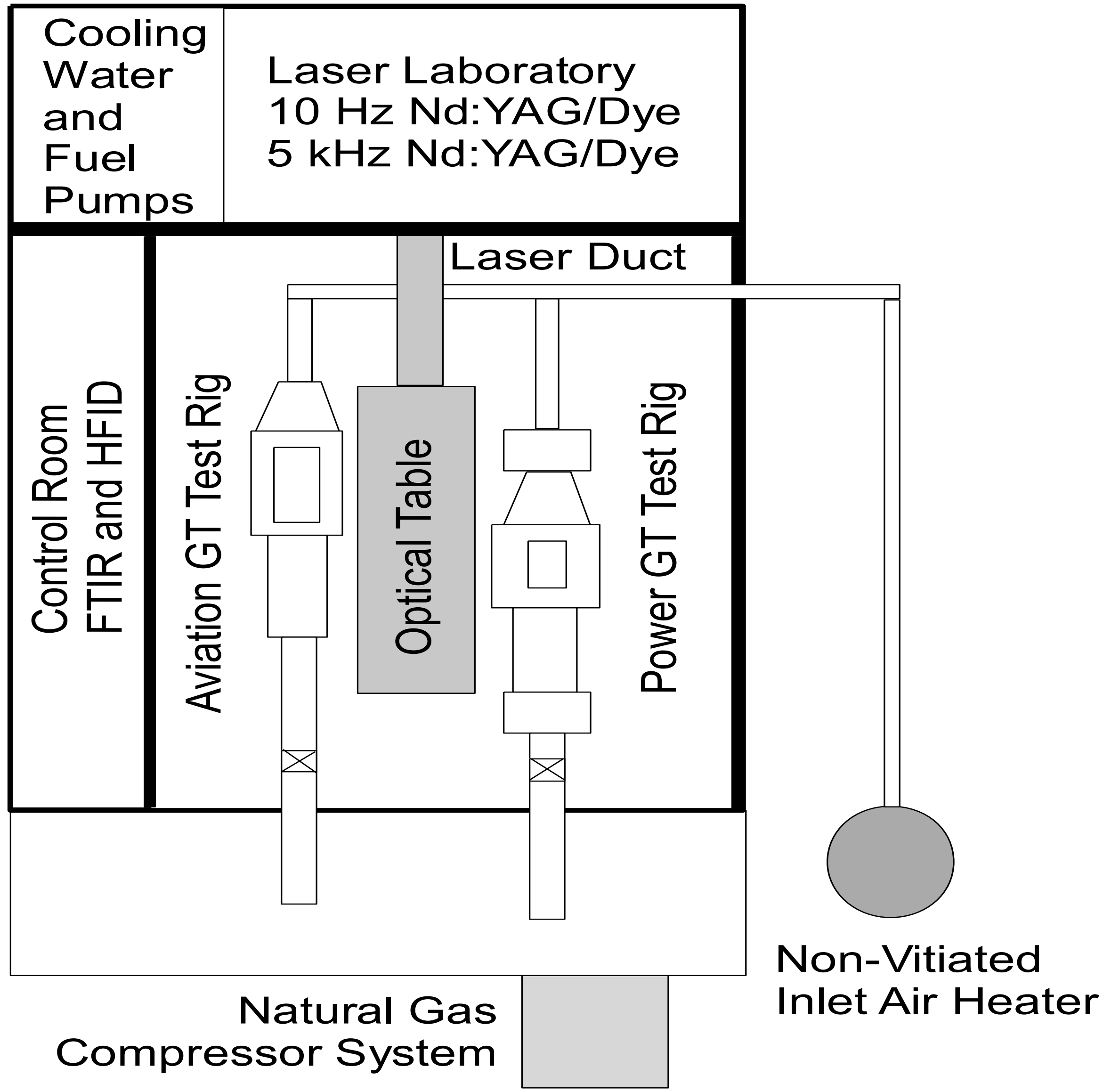
Purdue Gas Turbine Combustion Facility (GTCF)



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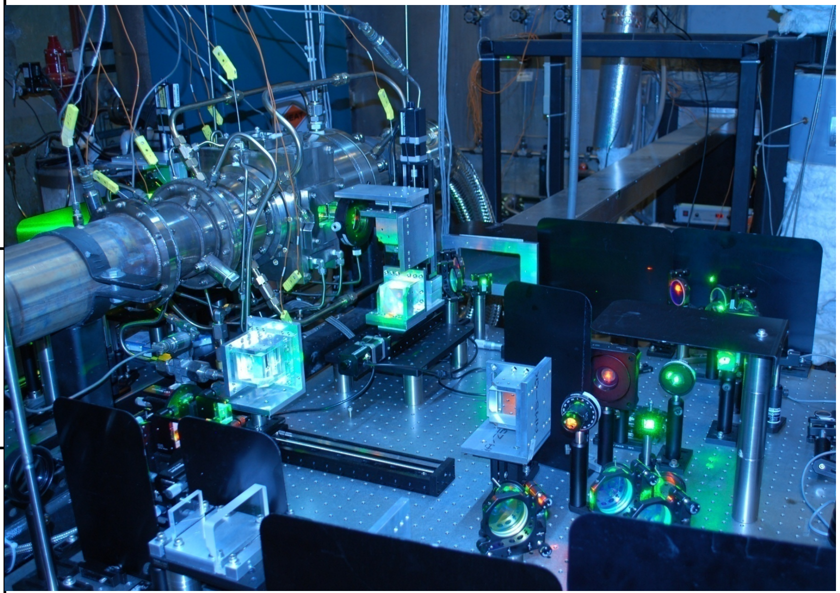
Purdue Gas Turbine Combustion Facility (GTCF)

High Pressure Lab System	Maximum Flow Capacity	Max Operating Condition
Natural Gas Heated High Pressure Air	9 lbm/sec	700 psi / 540 deg C 1000 deg F
Electric Heated Air or Nitrogen	1 lbm/sec	600 psi / 600 deg C
Nitrogen	2 to 5 lbm/sec	1,500 psi
Liquid Aviation Fuel (Kerosene)	1 lbm/sec/tank (2 tanks)	1,500 psi
Natural Gas	1 lbm/sec	3500 psi



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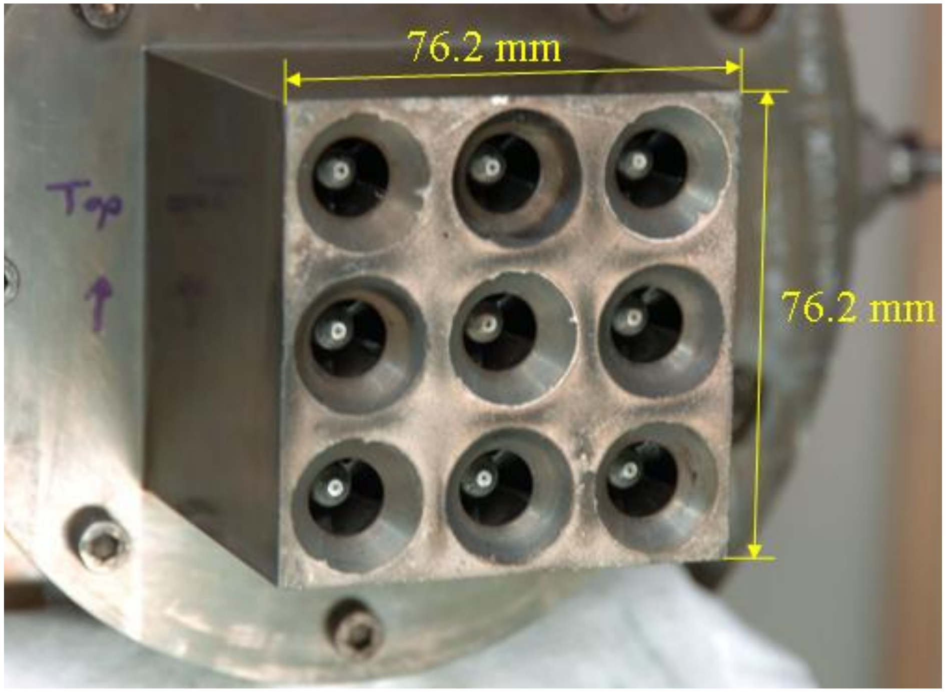
NASA 9-Point LDI Assembly (Top-Hat)

- **Nine simplex injectors arranged at throats of nine converging-diverging venturis in a 3 x 3 arrangement.**

- **Axial swirlers with helical vanes at 60° impart swirl to incoming heated air.**

- **Only central injector used for testing.**



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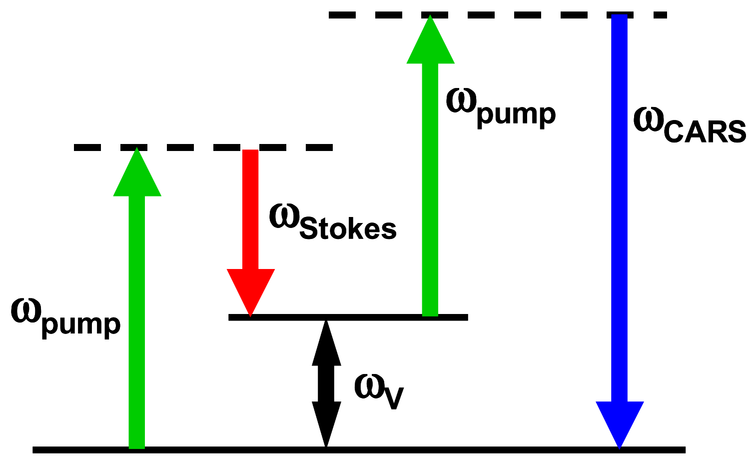
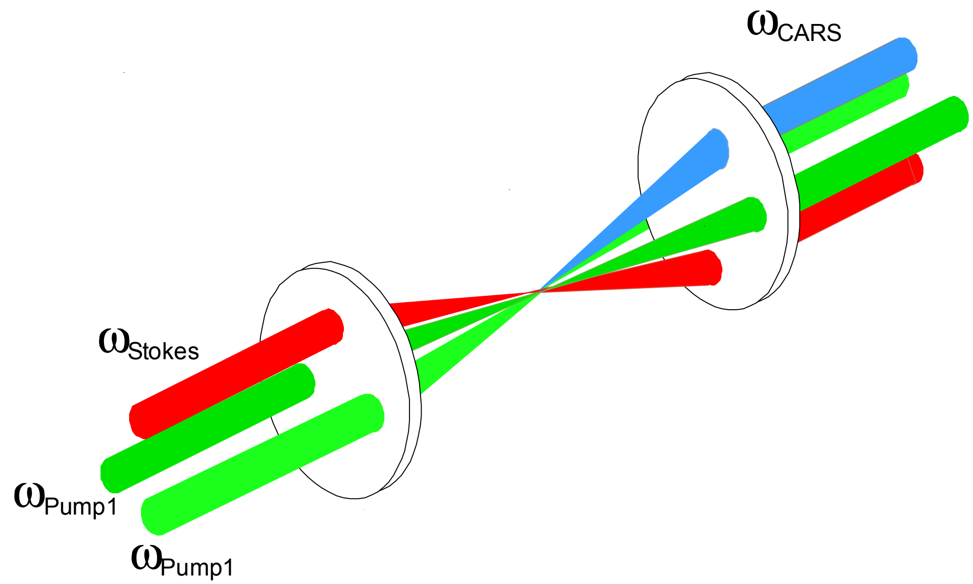
Coherent Anti-Stokes Raman Scattering (CARS)

- Conventional "Single-Pump" CARS
- Noninvasive
- Coherent Laser-Like Signal
- Spatially and Temporally Resolved
- Excellent Gas Temperature Data (especially at higher temperatures)





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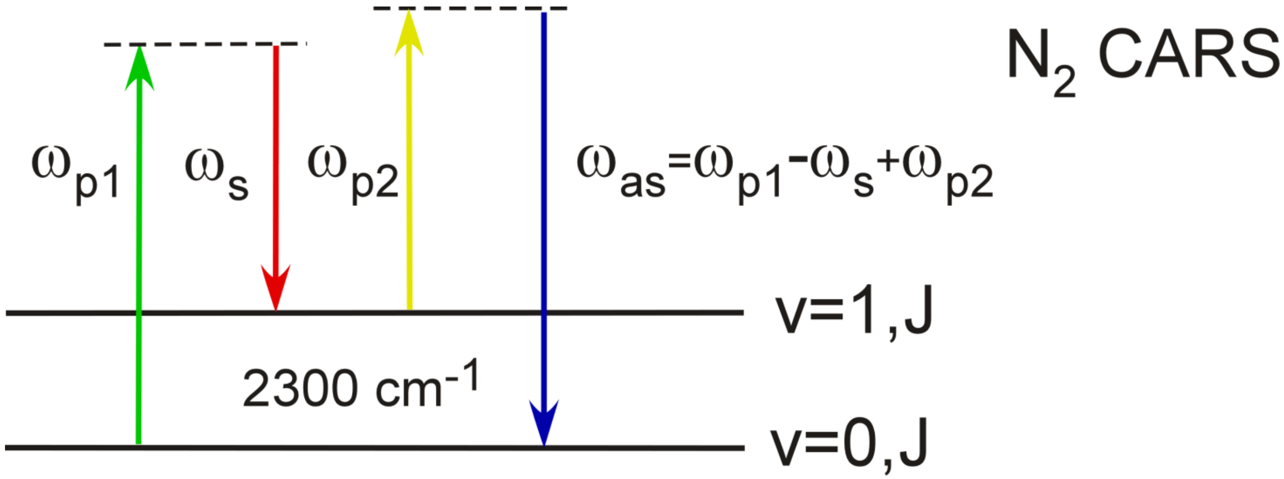
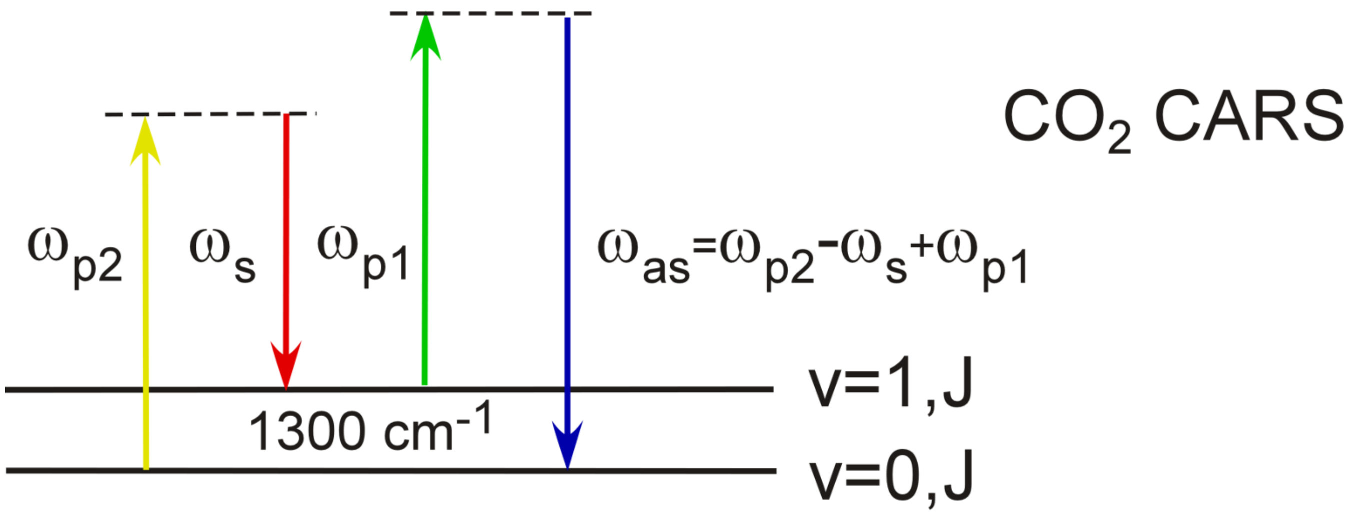
Dual-Pump CARS of N_2/CO_2





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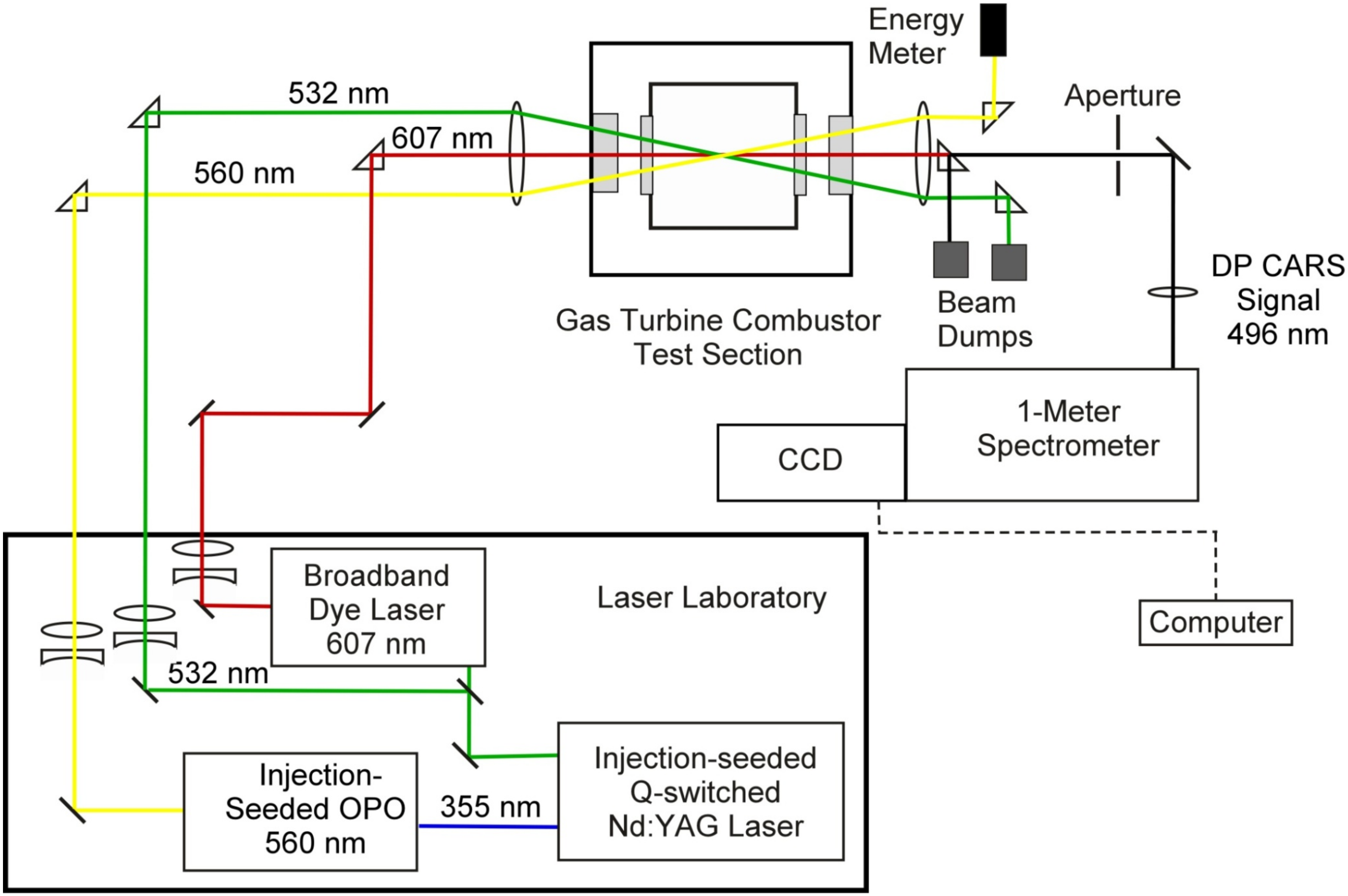
Overall Experimental System



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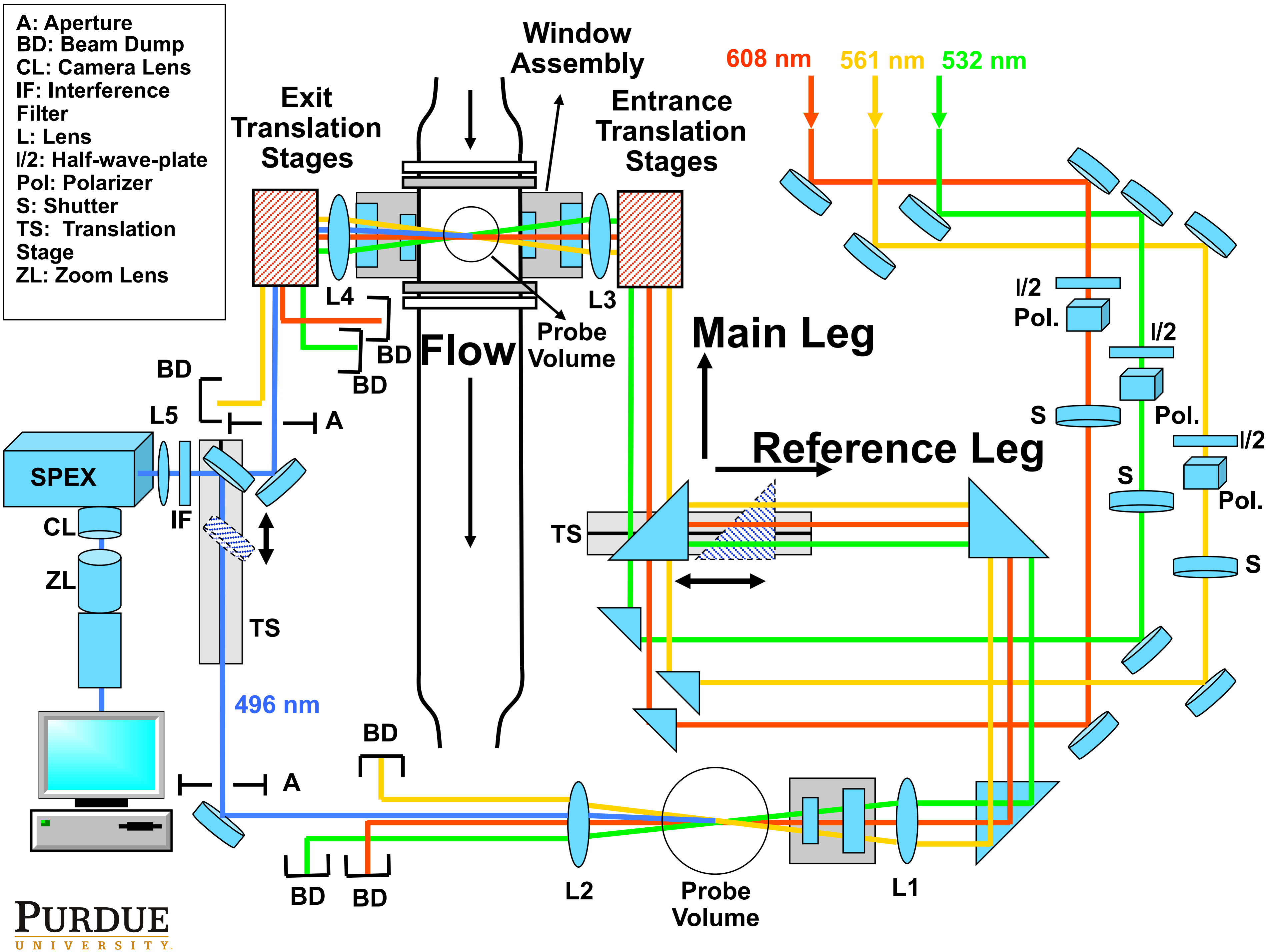
Measurement Challenges in GTCF

- **Translation of probe volume inside the flame zone.**
- **Installation of pin-hole for spatial overlap of CARS beams not possible, must use referemce leg alignment.**
- **Measurement of non-resonant signal in the reference leg for spectral normalization of CARS signal.**
- **Safety of thin window, CARS beams are focused tightly in the middle of the test section.**


A: Aperture
BD: Beam Dump
CL: Camera Lens
IF: Interference Filter
L: Lens
l/2: Half-wave-plate
Pol: Polarizer
S: Shutter
TS: Translation Stage
ZL: Zoom Lens
Window Assembly
Exit Translation Stages
Entrance Translation Stages
608 nm
561 nm
532 nm
L4
L3
BD
BD
Flow
Probe Volume
Main Leg
Reference Leg
l/2
Pol.
S
BD
A
L5
SPEX
IF
CL
ZL
TS
TS
496 nm
BD
A
BD
BD
L2
Probe Volume
L1
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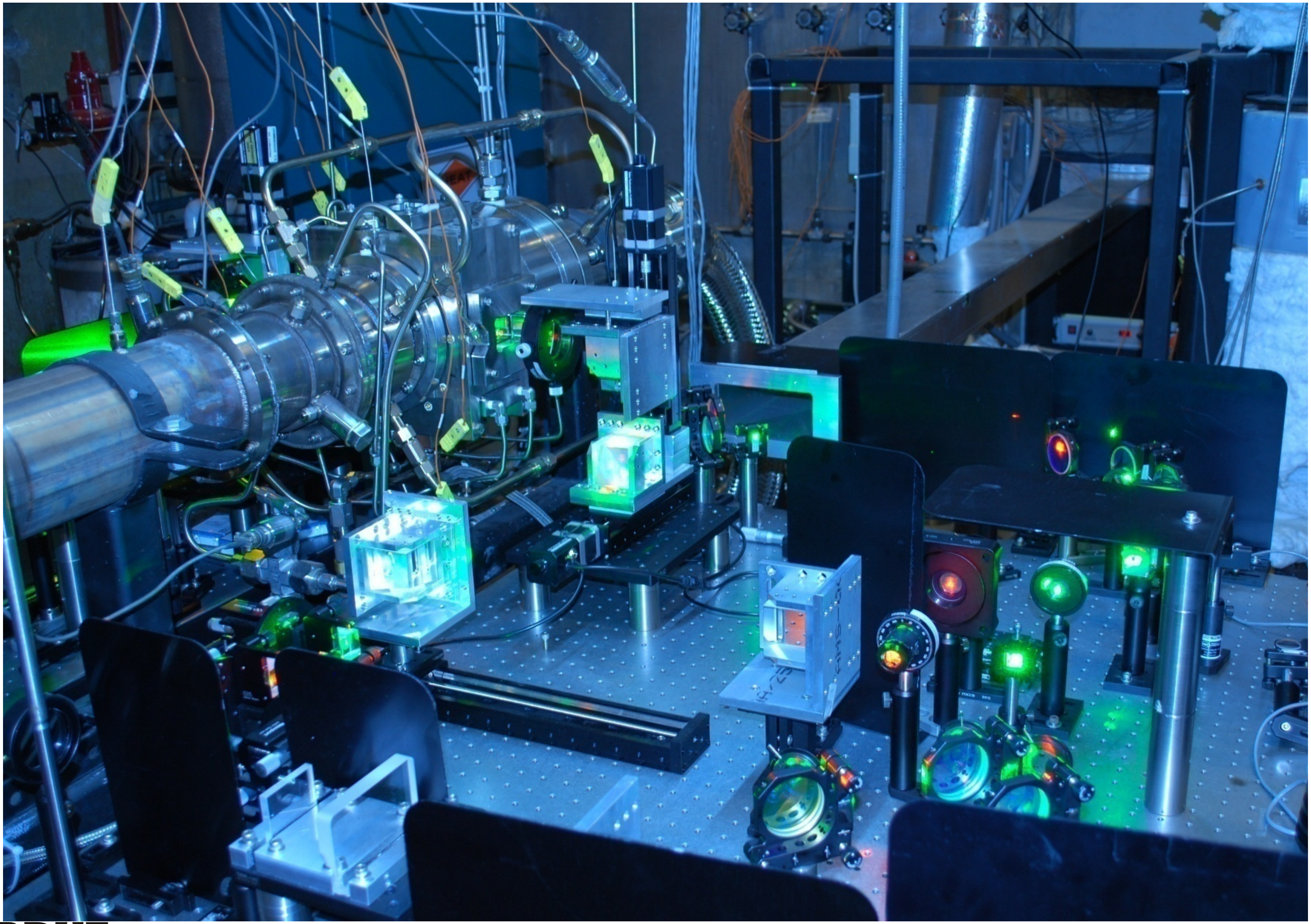
Optical System near GTCF

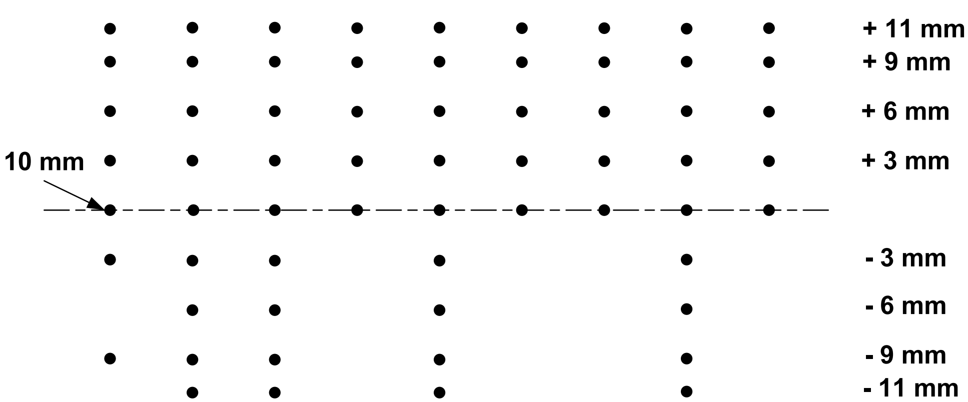


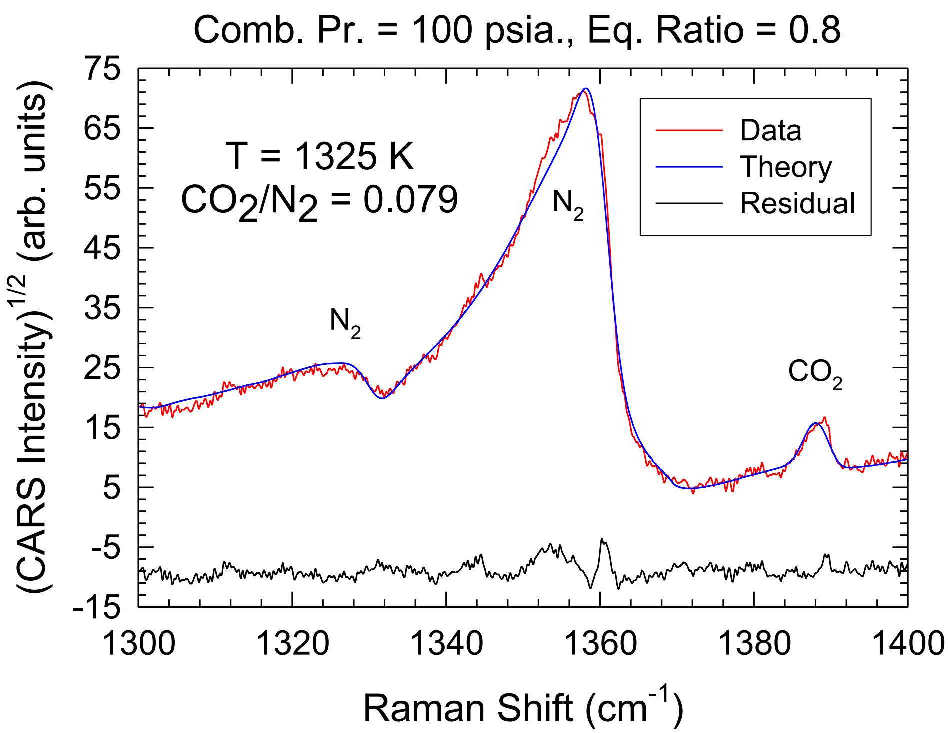
Operating Conditions, Measurement Locations and Sample DP-CARS Spectra

	Φ=0.4	Φ=0.59	Φ=0.80	Φ=1.0
100 psia *(7.0 atm.)*	■	■	■	■
125 psia *(8.5 atm.)*	■			
150 psia *(10 atm.)*	■			

- Burner Inlet Temperature: 850 ^{0}F (725 K)
- Fuel: Jet-A
- Normalized injector pressure drop = 4%

F = 0.6
P = 100 psi
DP/P = 4%
Note: Distance between points along the centerline is 5 mm





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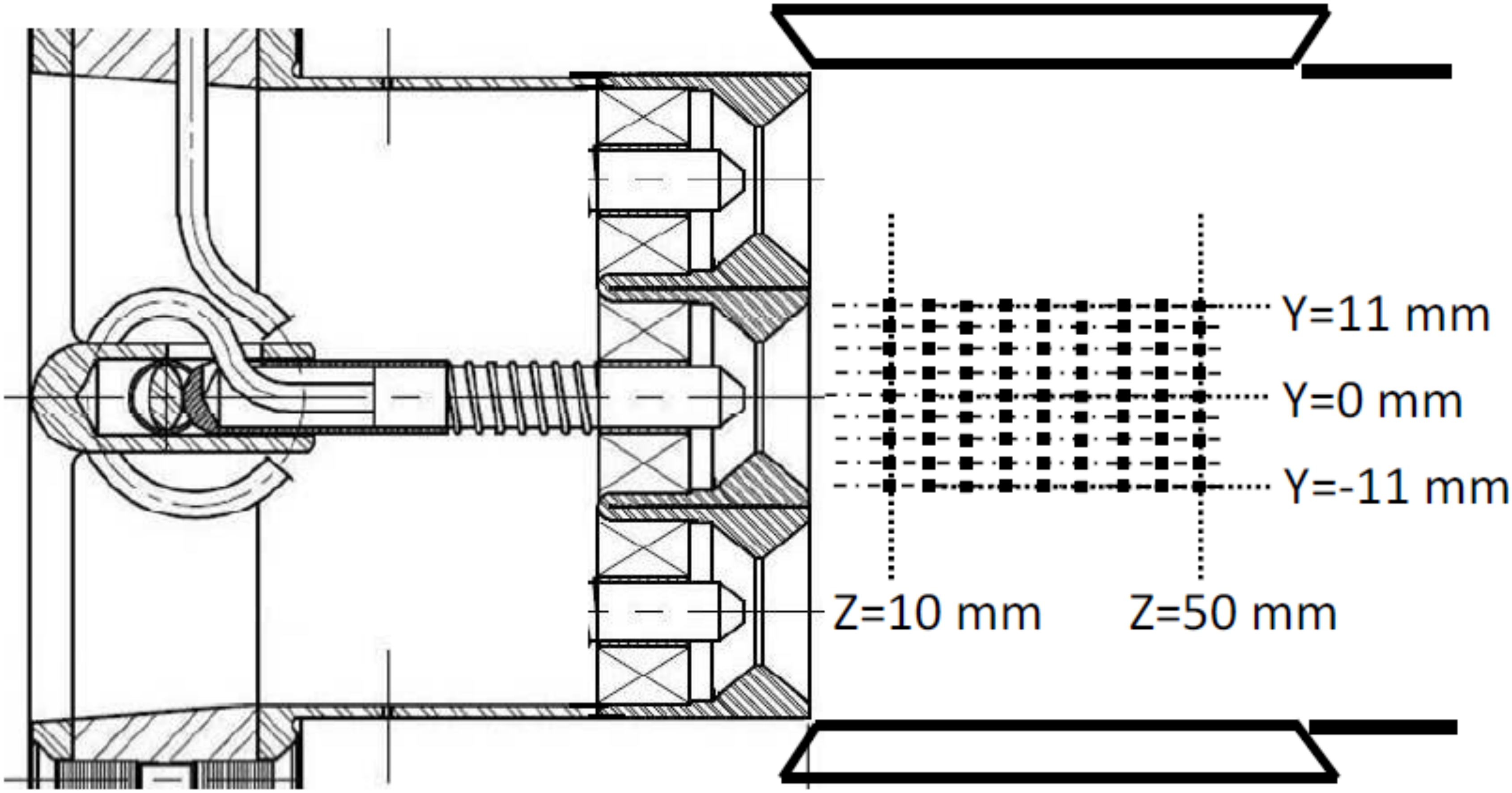
Measurement Grid for DP-CARS



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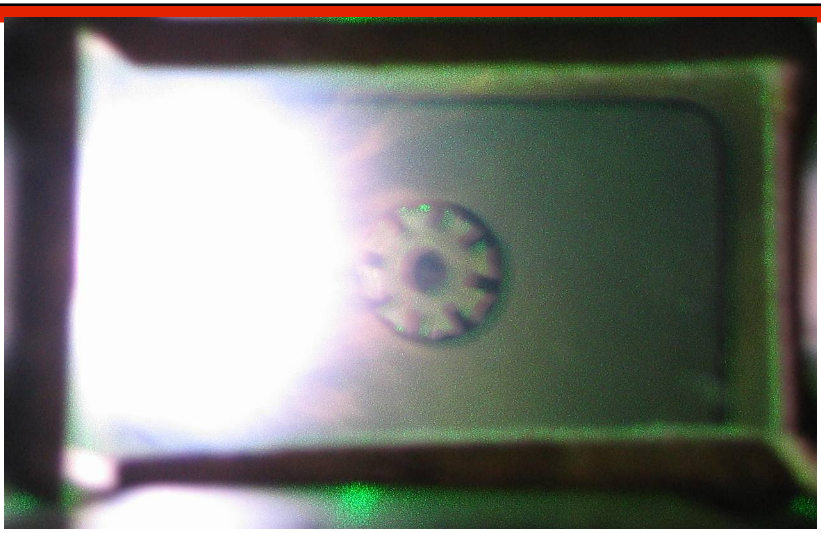
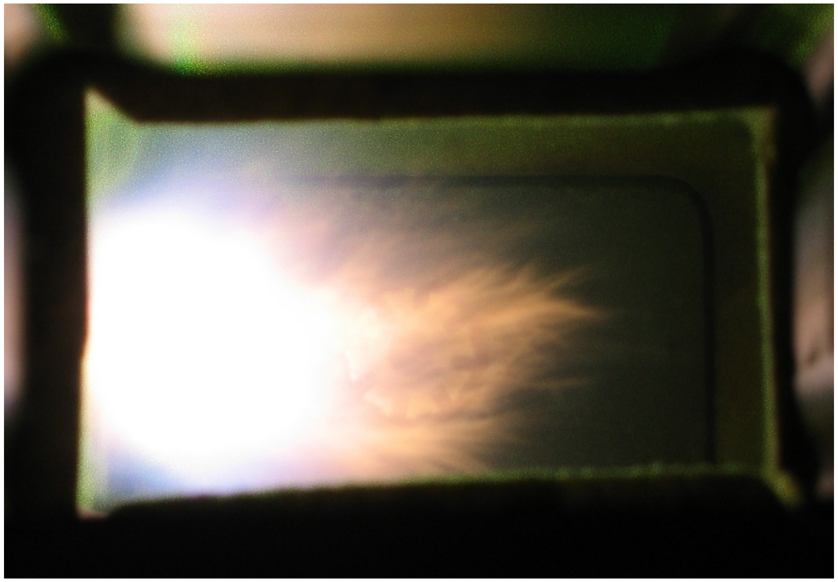
Flame Characteristics @ 100 psia



Φ =0.4

Φ =0.59



Φ =0.8

Φ =1.0

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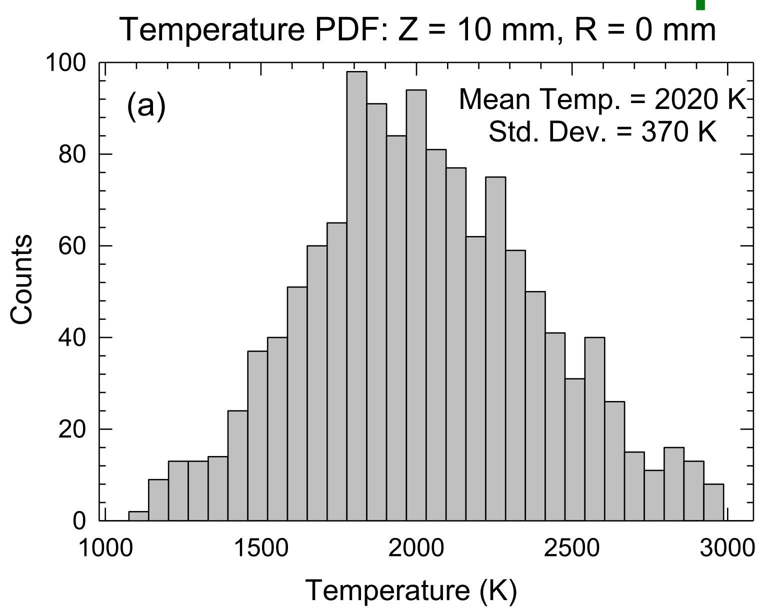
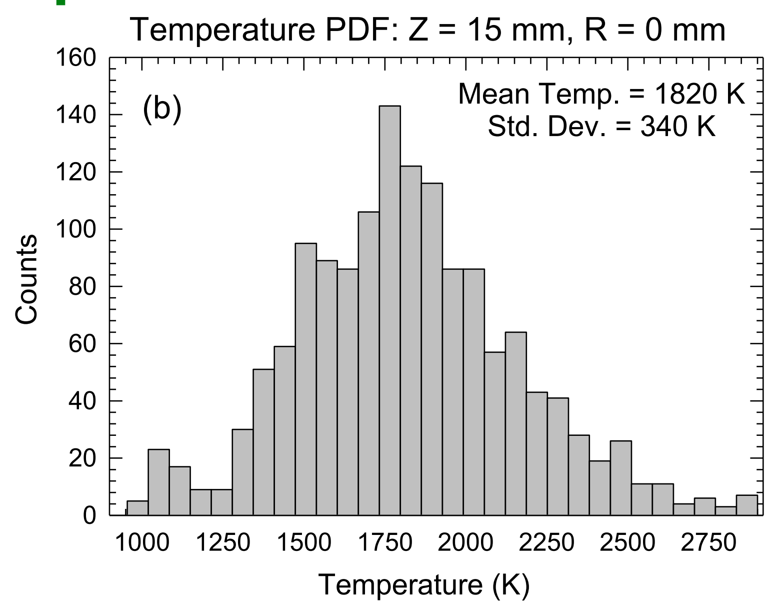
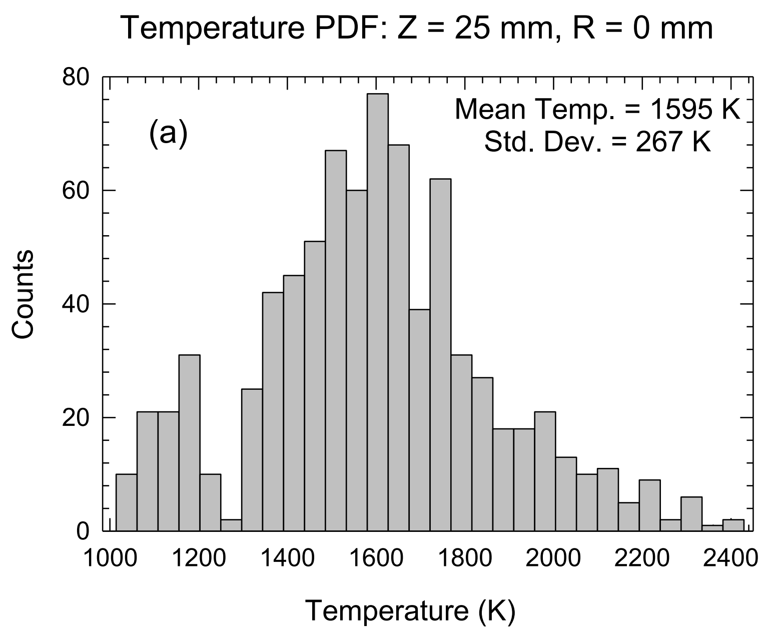
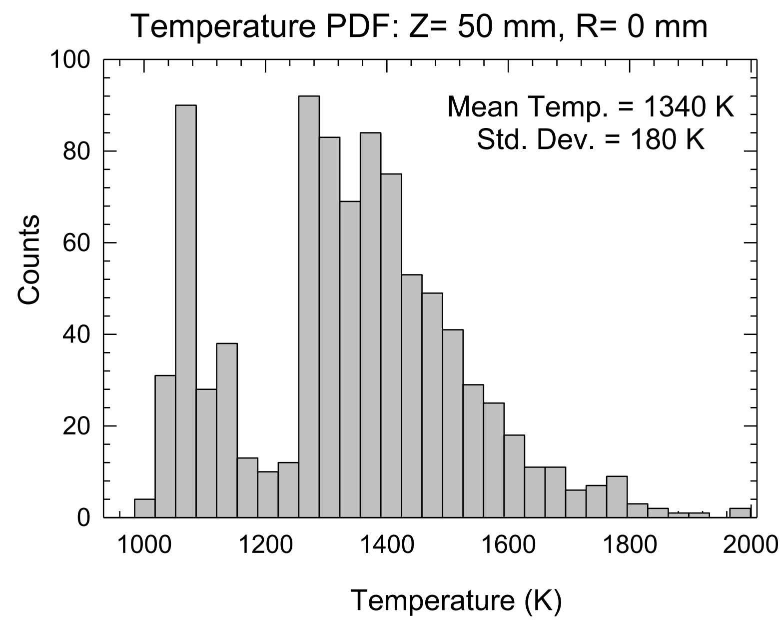
Temp PDFs Along Centerline

Combustor Pressure: 104 psia, Equivalence Ratio: 0.4









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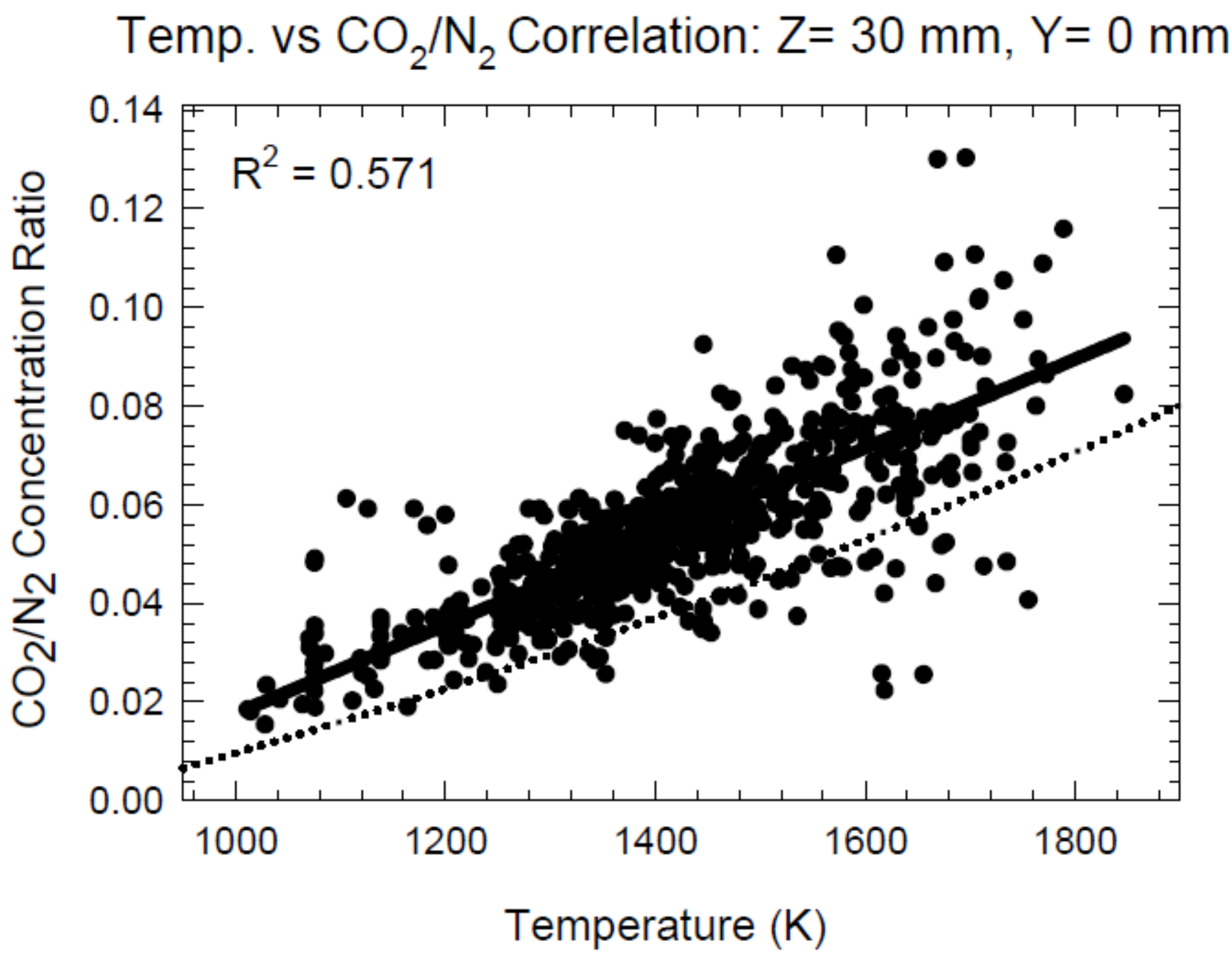
Temperature and CO_2/N_2 Correlation Plot

Combustor Pressure: 150 psia., Equivalence Ratio: 0.48



----- Adiabatic Equilibrium

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Accomplishments and Conclusions

- A new OPO/PDA system was used to generate the 560-nm pump beam in the dual-pump CARS system. Considerable care in laser system alignment was required to obtain good beam quality in the combustor test cell.
- The Zaber translation stages performed well, alignment was maintained over the entire spatial region of interest during the test.
- The reference leg was invaluable for alignment and for frequent recording of the nonresonant signal. Alignment was maintained before and after translation of the large 2-inch prisms.

Accomplishments and Conclusions

- Estimated uncertainty in temperature measurements :
  - Accuracy: 1-2%
  - Precision: 2-3%
- Uncertainty in CO_2/N_2 ratio measurements :
  - Very dependent on CO2 concentration and on the temperature, approximately 10% relative standard deviation in the range of 5% CO_2 concentration around 1500 K.
- Probe volume dimensions:
  - 500-600 µm (FWHM) along the laser propagation direction.
  - 50 µm perpendicular to the laser direction.

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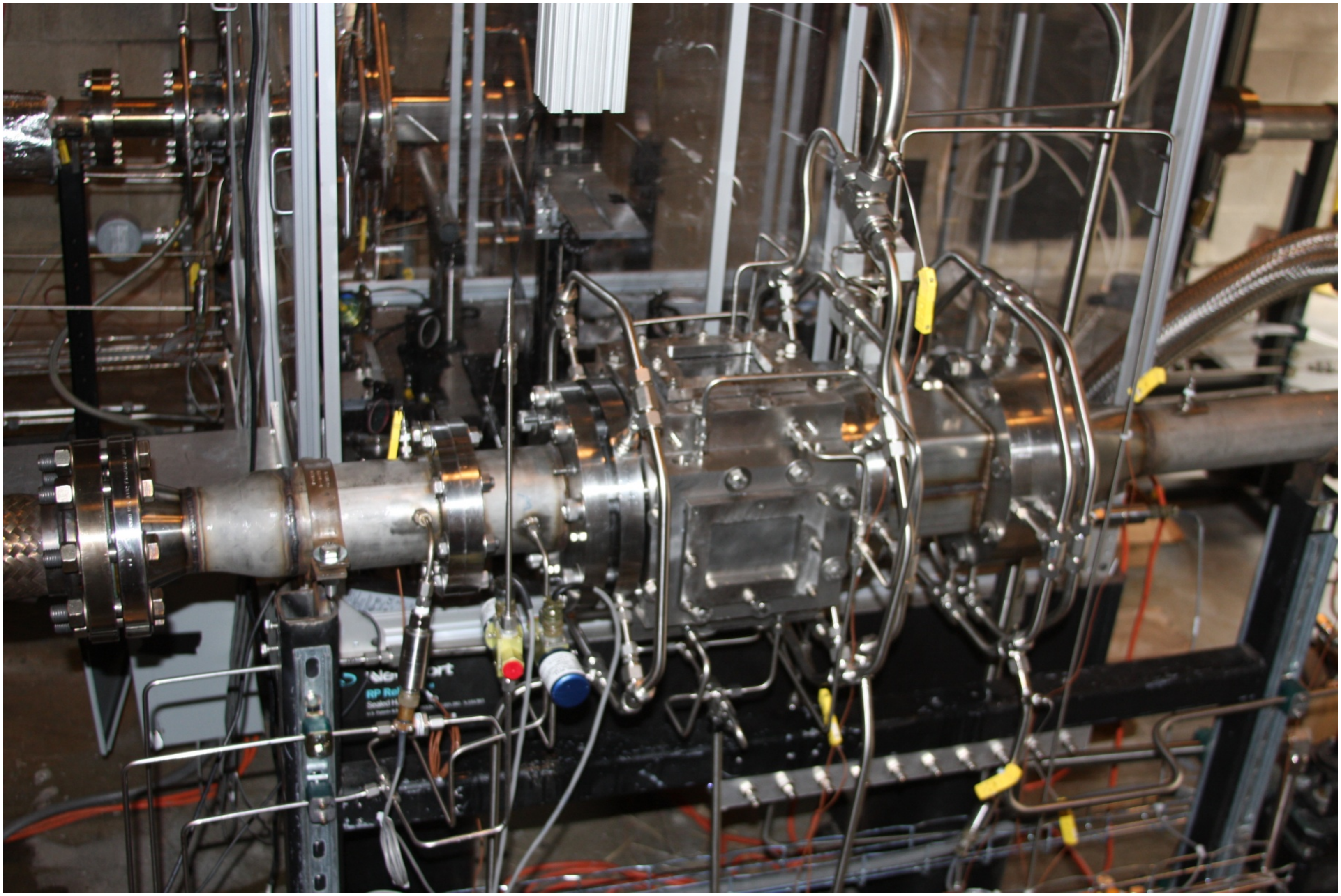
Modified Combustor Window Assembly

- Cross section increased from 3"x3“ to 4.2"x4.2". The modified CWA is fabricated from Hastelloy-X instead of stainless steel. Brazing has been eliminated. Film cooling air passages are incorporated in the injector assembly rather than in the CWA. Thermal barrier coatings are being applied to the window assembly inner surfaces.

- Upstream spool section has been redesigned to accommodate the larger injectors and to ensure uniform flow into the injector.

- Downstream spool sections redesigned for larger flow cross section.

Test Rig with Modified Combustor Window Assembly (CWA) Installed



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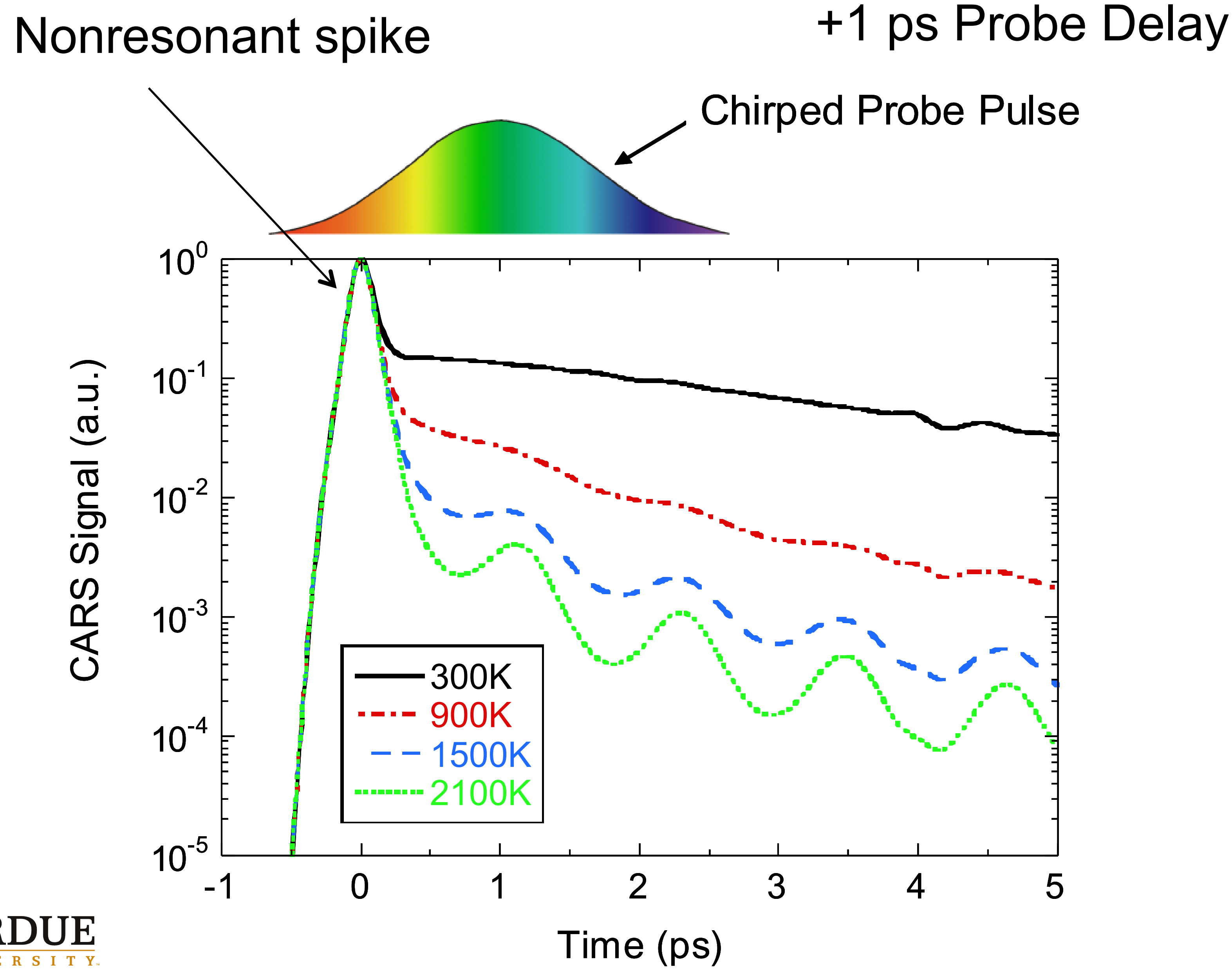
Single-Shot CPP fs CARS



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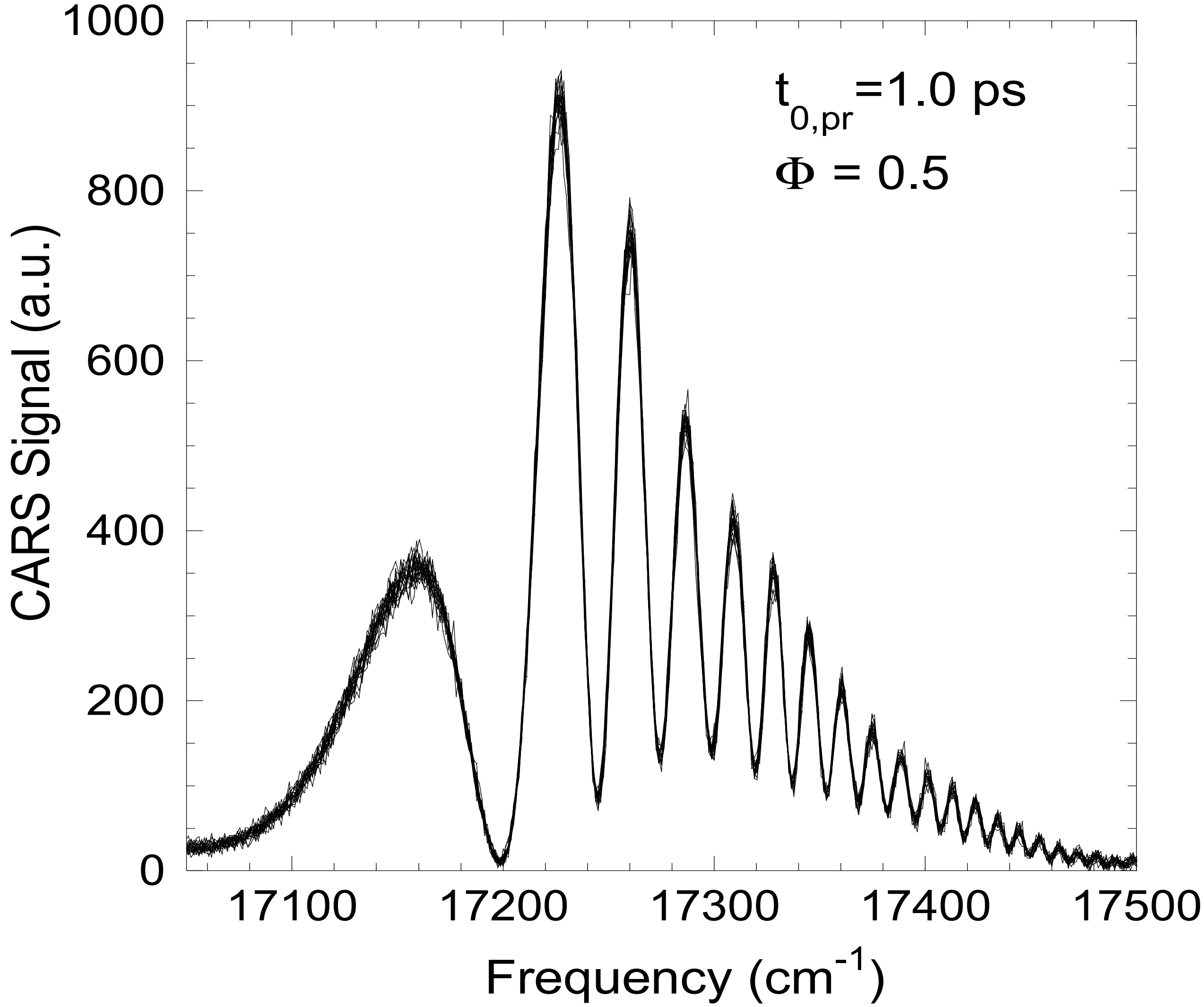
20 Single-Shots with Chirped Probe Pulse



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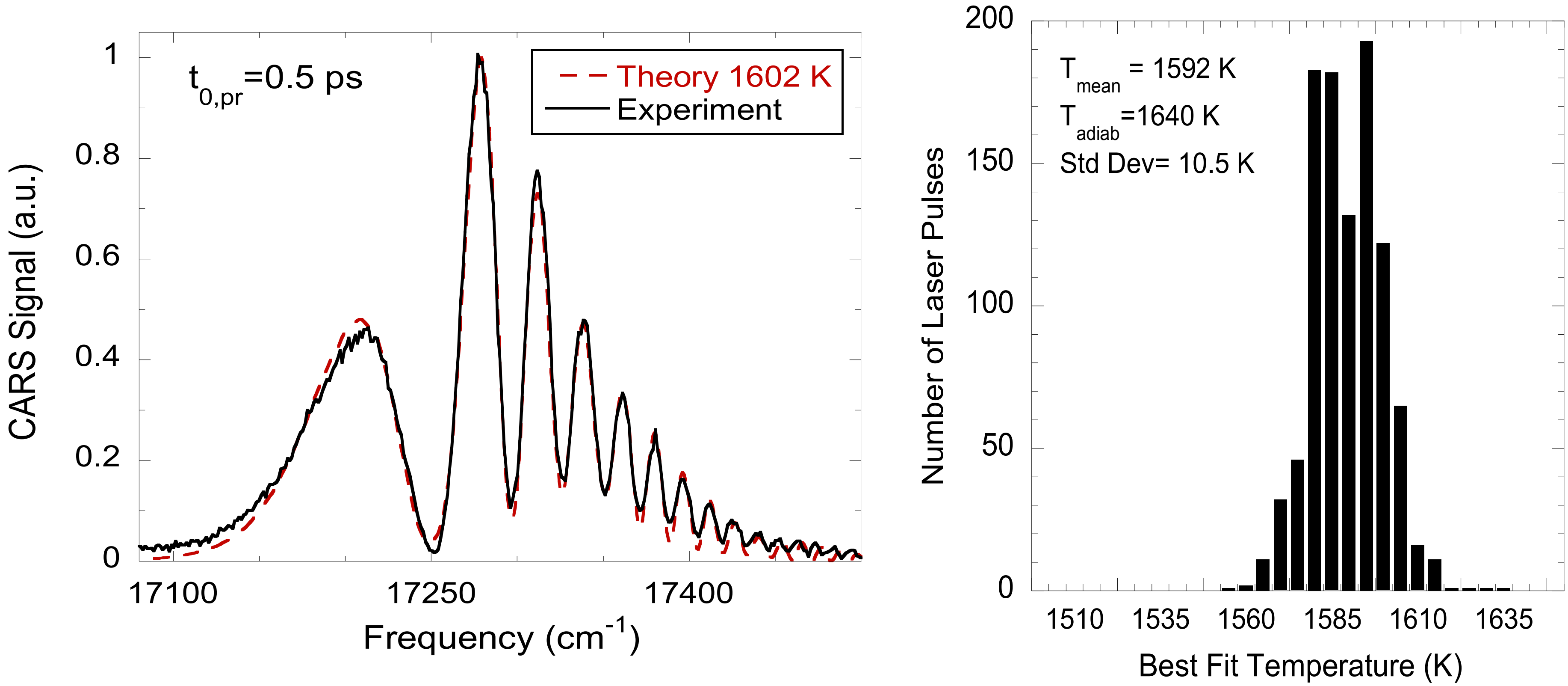
Temperature Histograms from Single-Shot fs CARS in Flames



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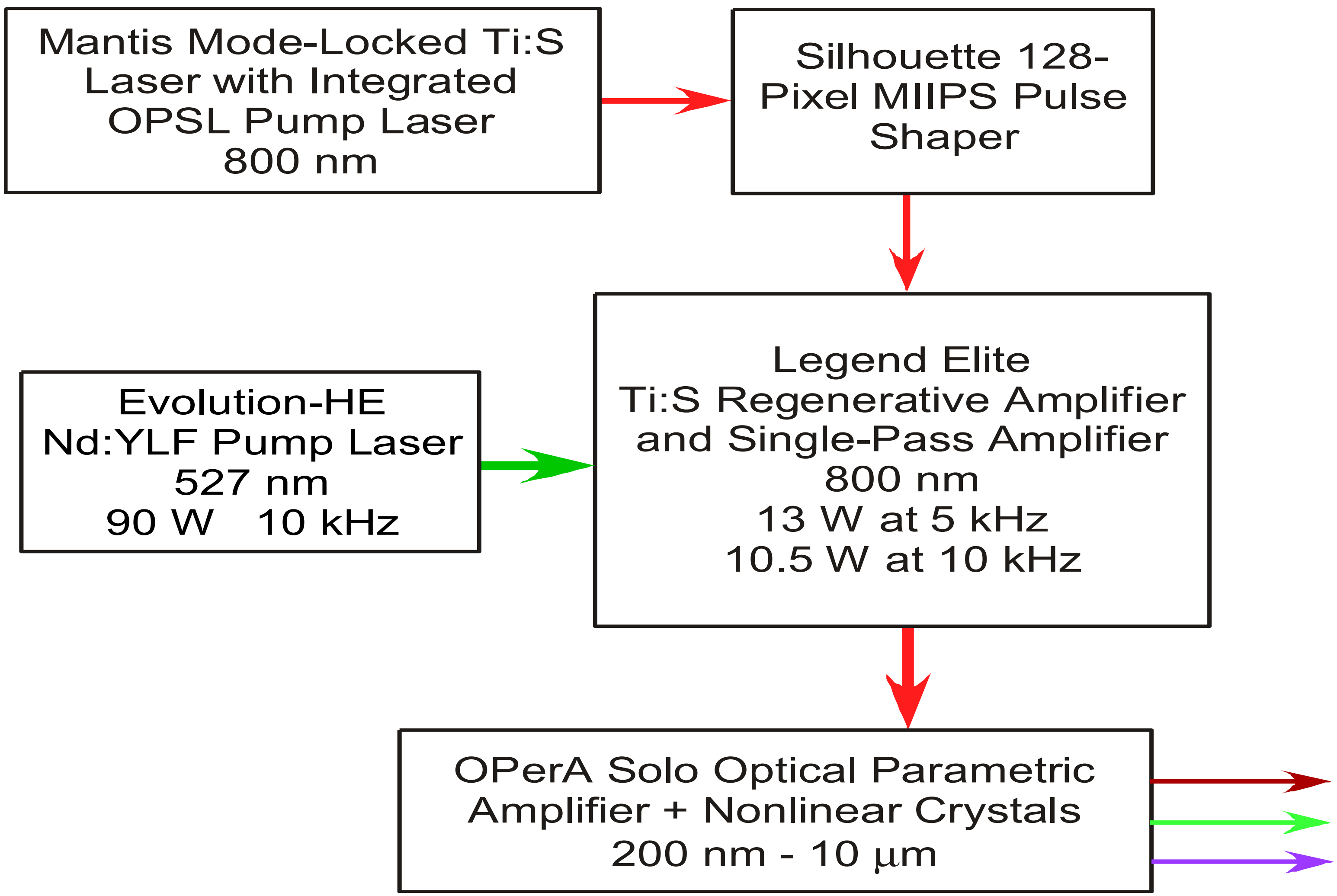
Single-Shot Temperature Measurements at 5 kHz

- New laser system from Coherent delivered to Purdue (AFOSR DURIP Program).
- Laser rep rate of either 5 kHz with 2.6 mJ per pulse or 10 kHz with 1.0 mJ per pulse.
- Pulse durations of either 60 fs or 30 fs.
- Pulse shaper integrated into the system between the oscillator and amplifier.

Single-Shot Temperature Measurements at 5 kHz: Coherent Ultrafast Laser System



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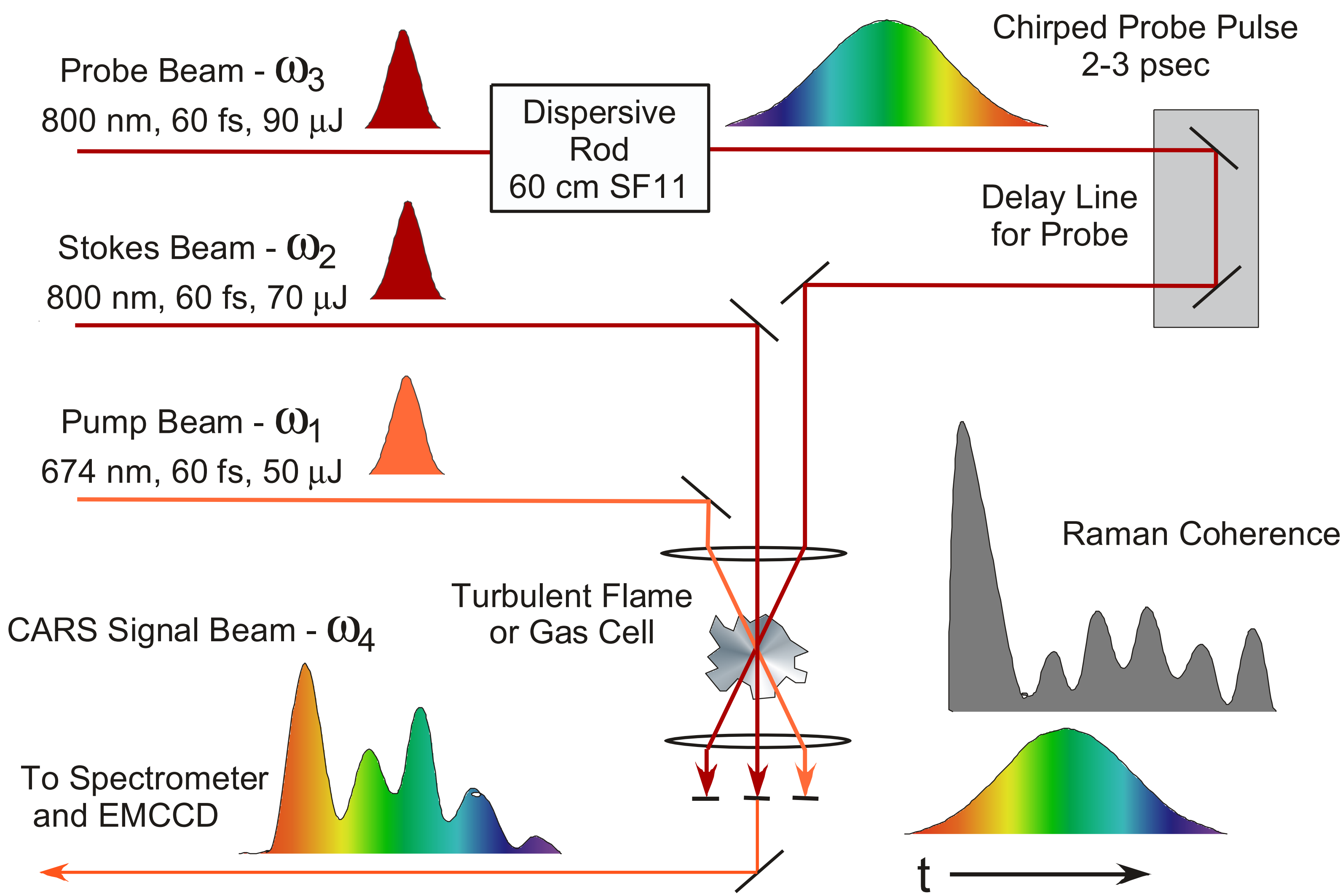
Single-Shot Temperature Measurements at 5 kHz

- Demo camera systems loaned by Princeton Instruments and Andor.
- Princeton Instruments system: 512x512 chip, physical mask, spectral acquisition from 66 rows by 512 columns, 5 kHz or 10 kHz spectral acquisition with charge in columns vertically binned.
- Andor system: 1024x1024 chip, optical mask, 50 rows by 1024 columns, 5 kHz spectral acquisition with charge in columns vertically binned, also have 512x512, 10 kHz system.

Single-Shot Temperature Measurements at 5 kHz



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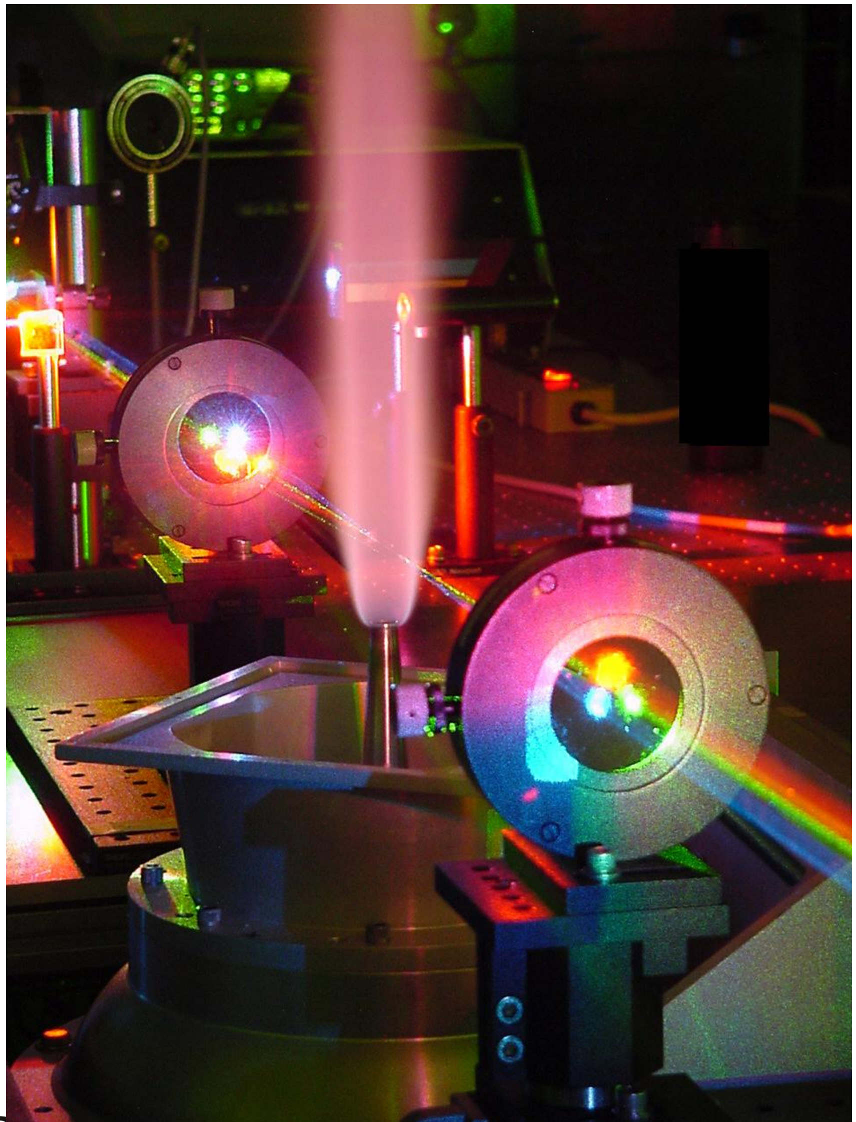
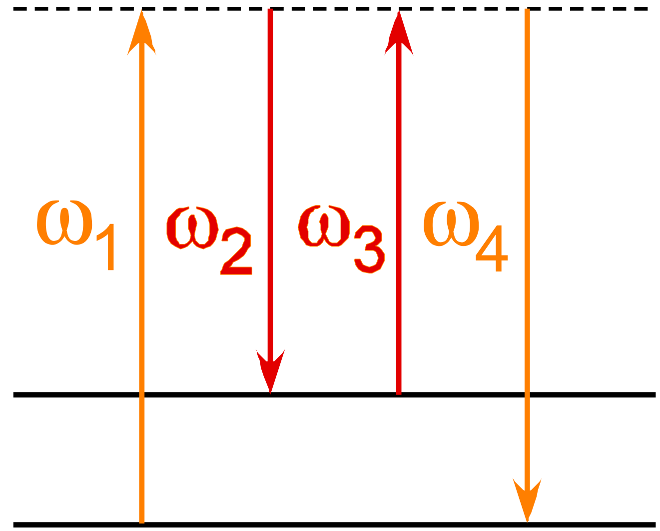
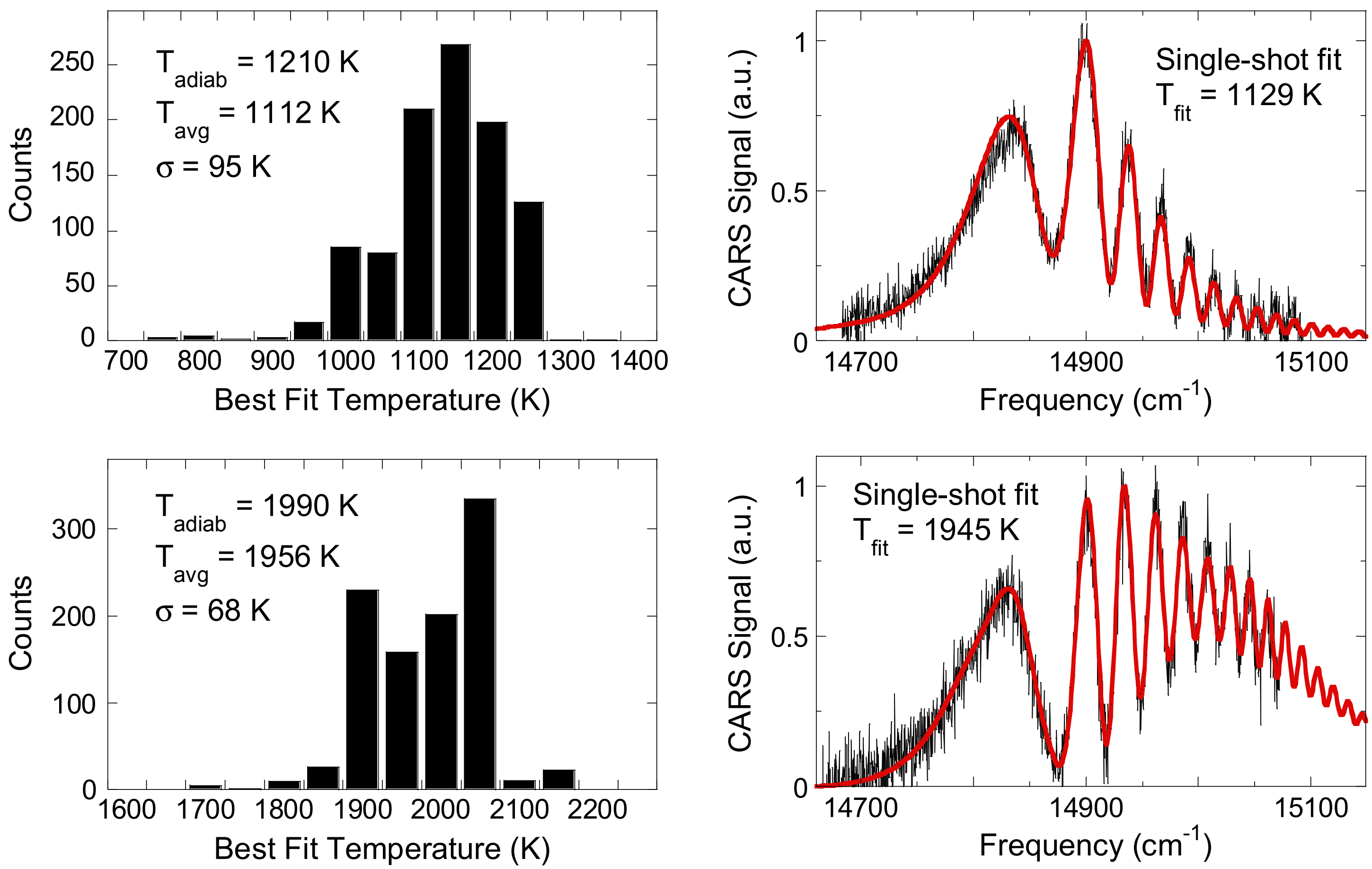
Single-Shot Temperature Measurements at 5 kHz





Single-Shot Temperature Measurements at 5 kHz

Hencken Burner Calibration Flames



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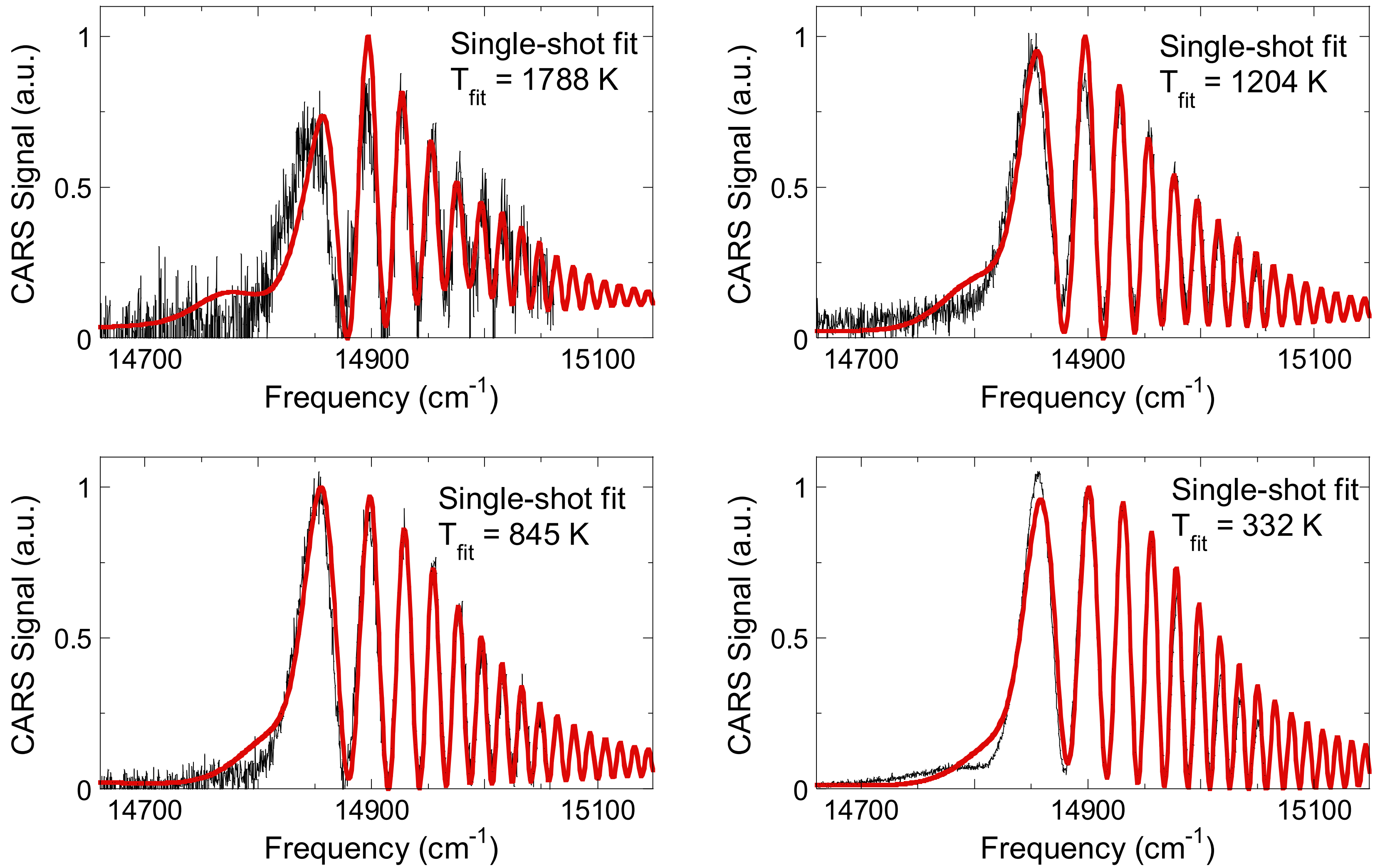
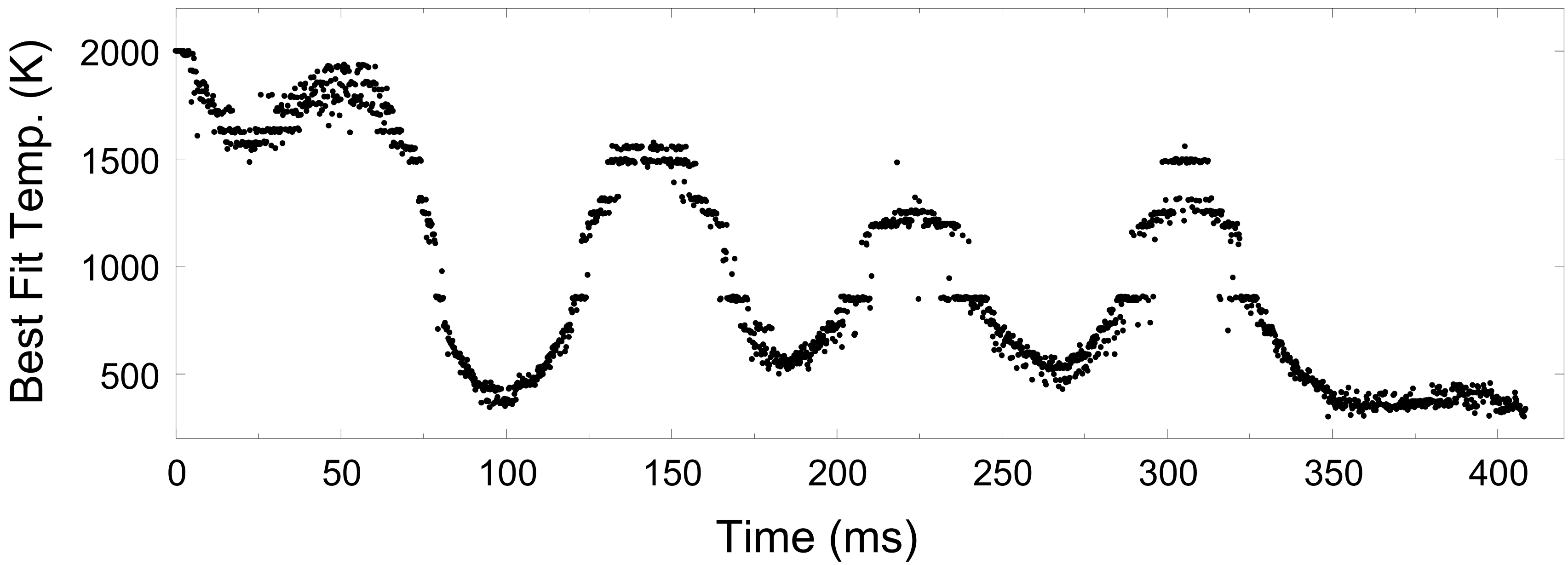
Single-Shot Temperature Meas at 5 kHz: Nonresonant Background Suppressed



Single-Shot Temperature Meas at 5 kHz: Nonresonant Background Suppressed



Conclusions: Fs CARS

- Temperature determined from single-shot fs CARS N_2 spectra recorded at 1 and 5 kHz from laminar, unsteady, and turbulent flames.
- Signals are very strong and reproducible from shot to shot. Precision ~~comparable to or~~ better than the best single-shot ns CARS systems.
- Theoretical model developed to fit CPP fs CARS spectra for temperature, accuracy of measurements can be improved. Main issue is incomplete characterization of the laser beams.
- CPP fs CARS concentration measurements in progress. Data analysis issues similar as for measurement of temperature.

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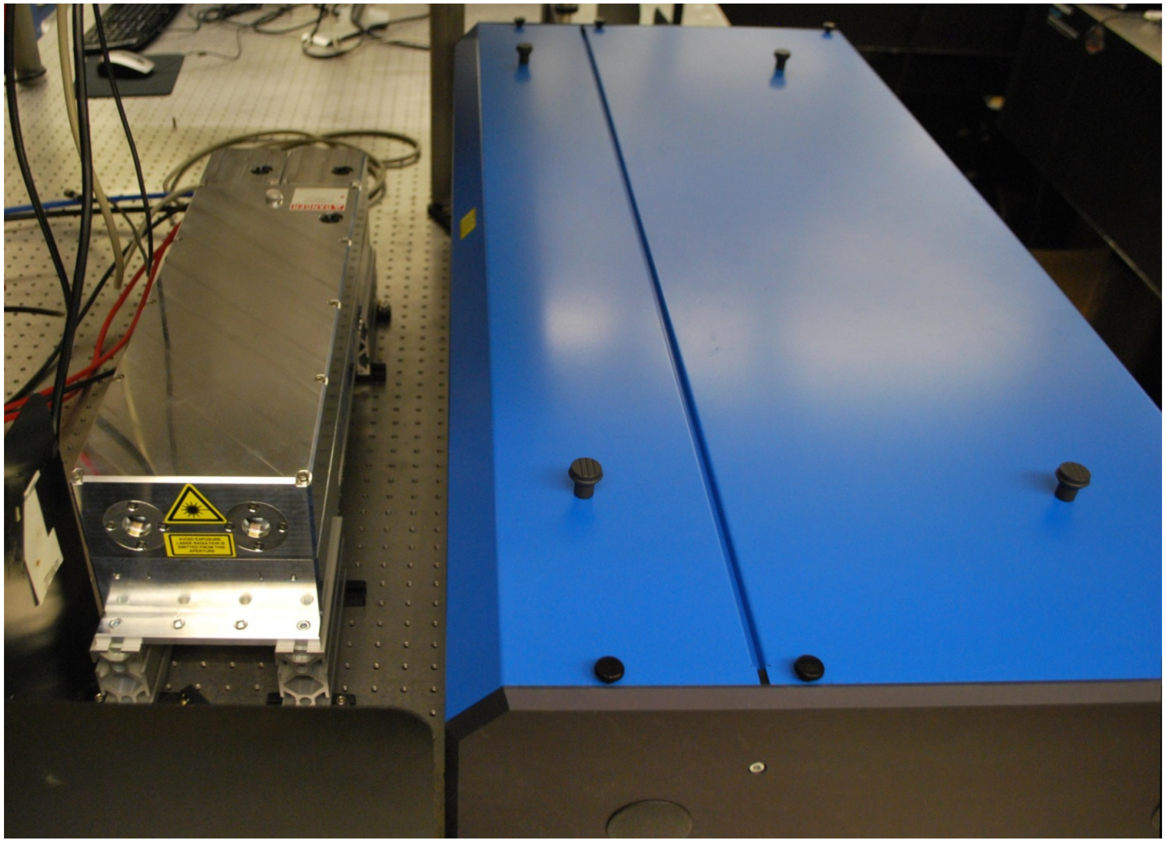
Future Work: fs CARS

- Temperature measurements in turbulent flames.
- Comparison of measurements with and without background suppression.
- Concentration measurements are still an open issue.
- More accurate characterization of the ultrafast laser pulses.
- Measurements in high pressure flames.
- Electronic resonance enhancement.

High-Repetition-Rate Diagnostic Techniques Based on Diode-Pumped Nd:YAG Lasers

- 10 kHz PIV – dual-head Edgewave laser
- 10 kHz OH PLIF – Credo dye laser pumped by the Edgewave laser

High-Repetition-Rate Laser System



Edgewave Diode-Pumped Solid State Nd:YAG Laser: 5 kHz Rep Rate, Dual-Head, 6 mJ/Pulse at 532 nm, 7 nsec Pulses

Sirah Credo Dye Laser
5 kHz Rep Rate, 500 mJ/ Pulse at 283 nm (2.5 W average power in UV)

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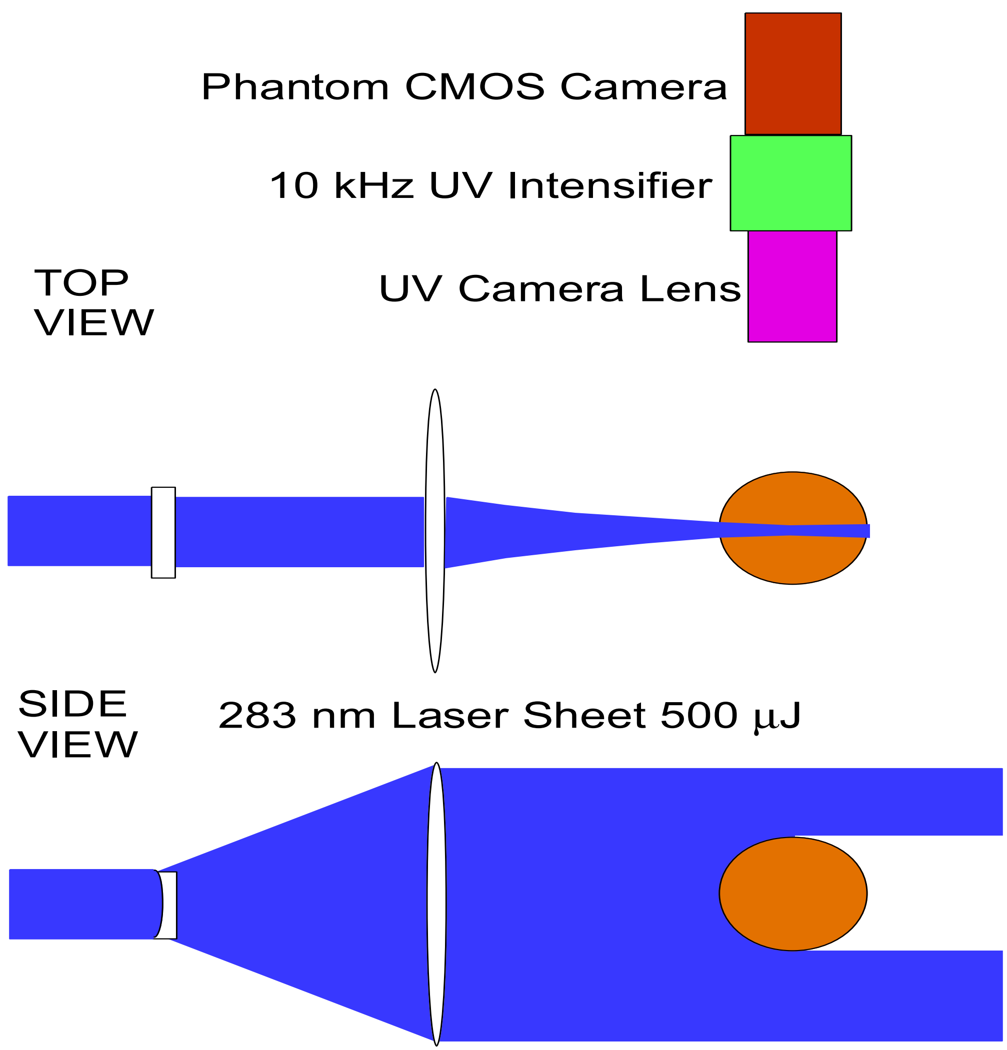
5 kHz OH PLIF of Liquid and Gelled Droplet Combustion



- Variety of gelled and liquid droplets have been investigated – methanol and JP8 fuels, HPC and aerosil gellants
- Drop sizes on the order of a few mm
- Combustion process is much more dynamic for the gelled droplets
- Effects of pressure investigated in optical cell

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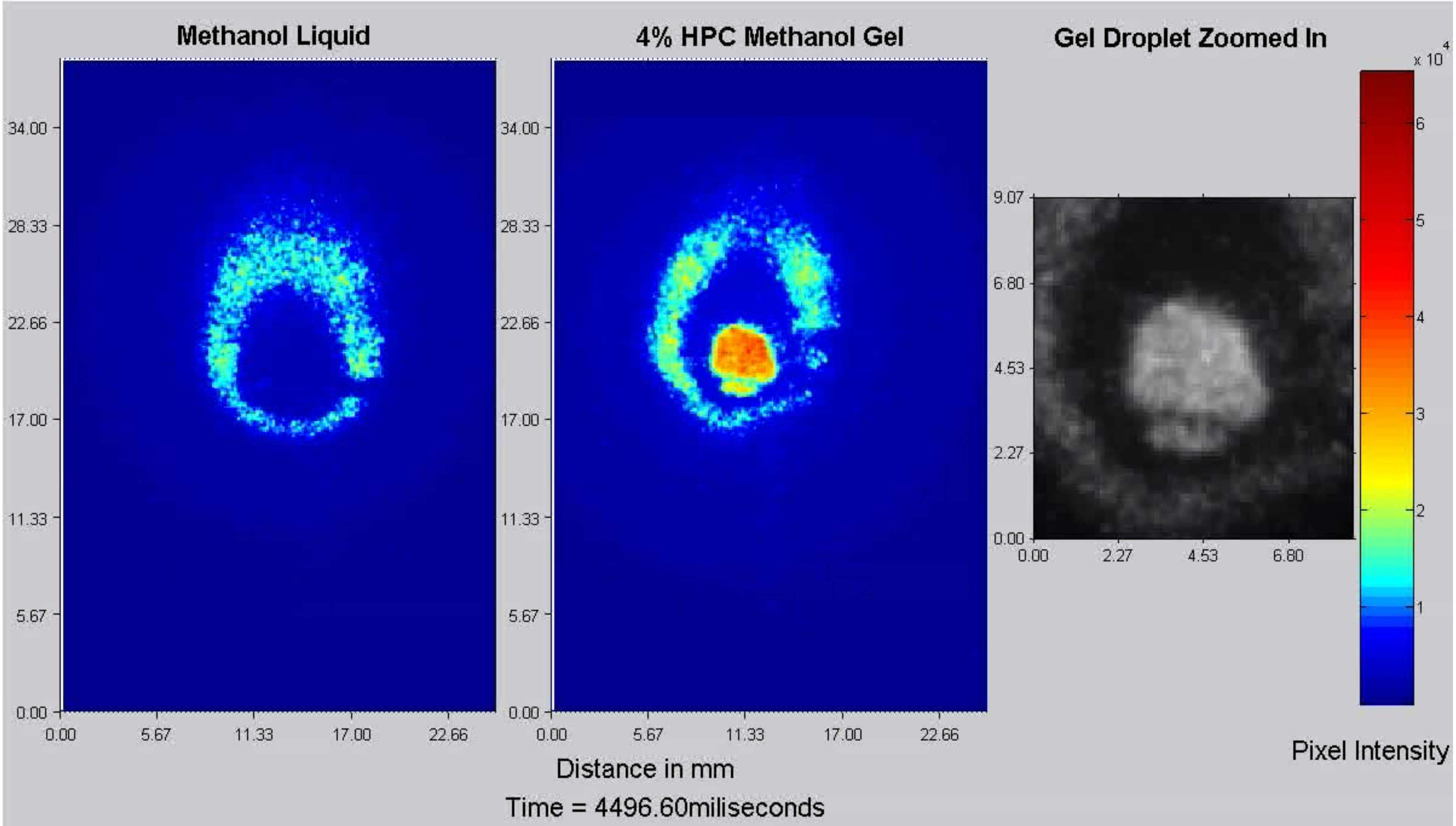
5 kHz OH PLIF of Liquid and Gelled Droplet Combustion



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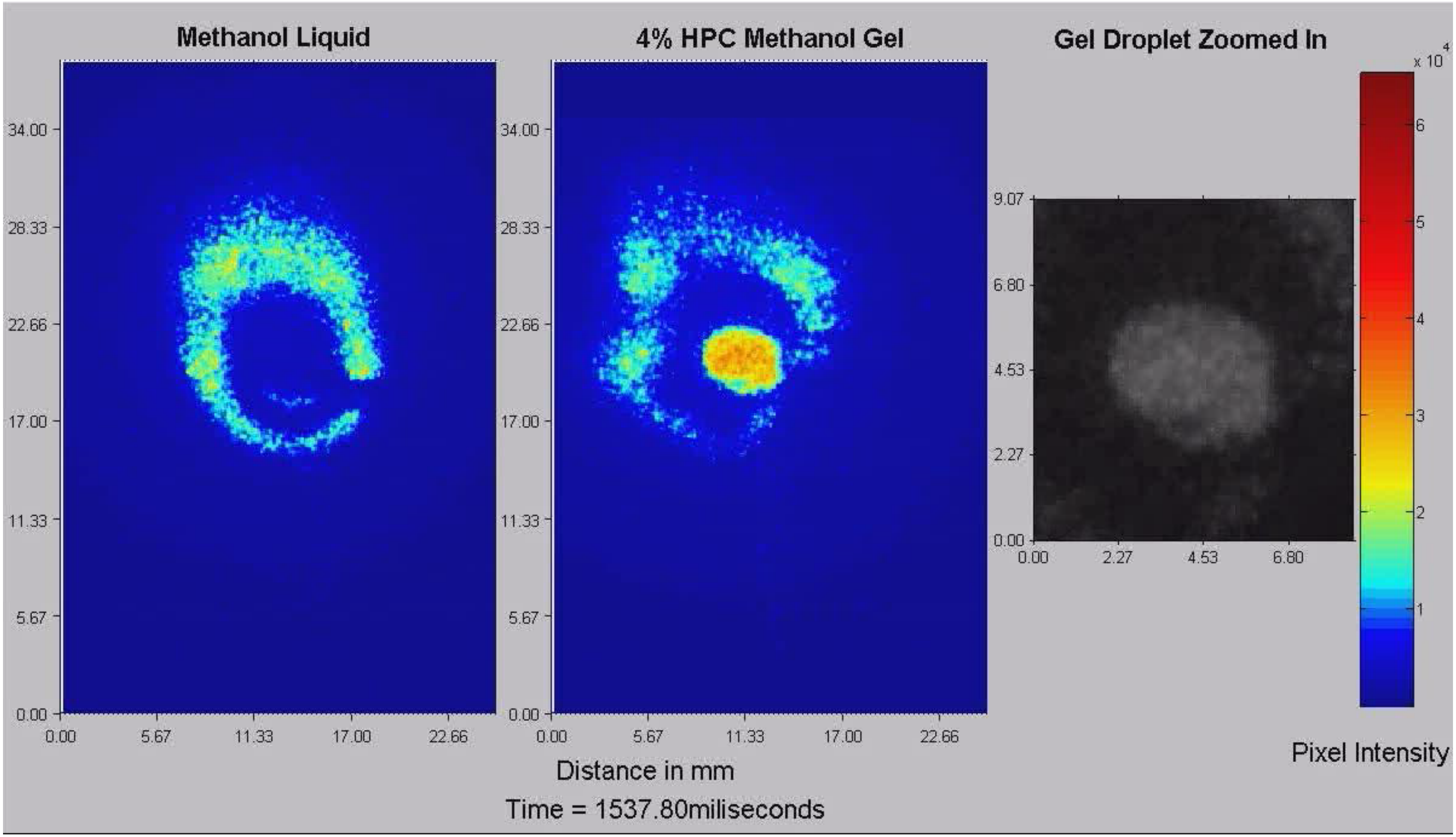

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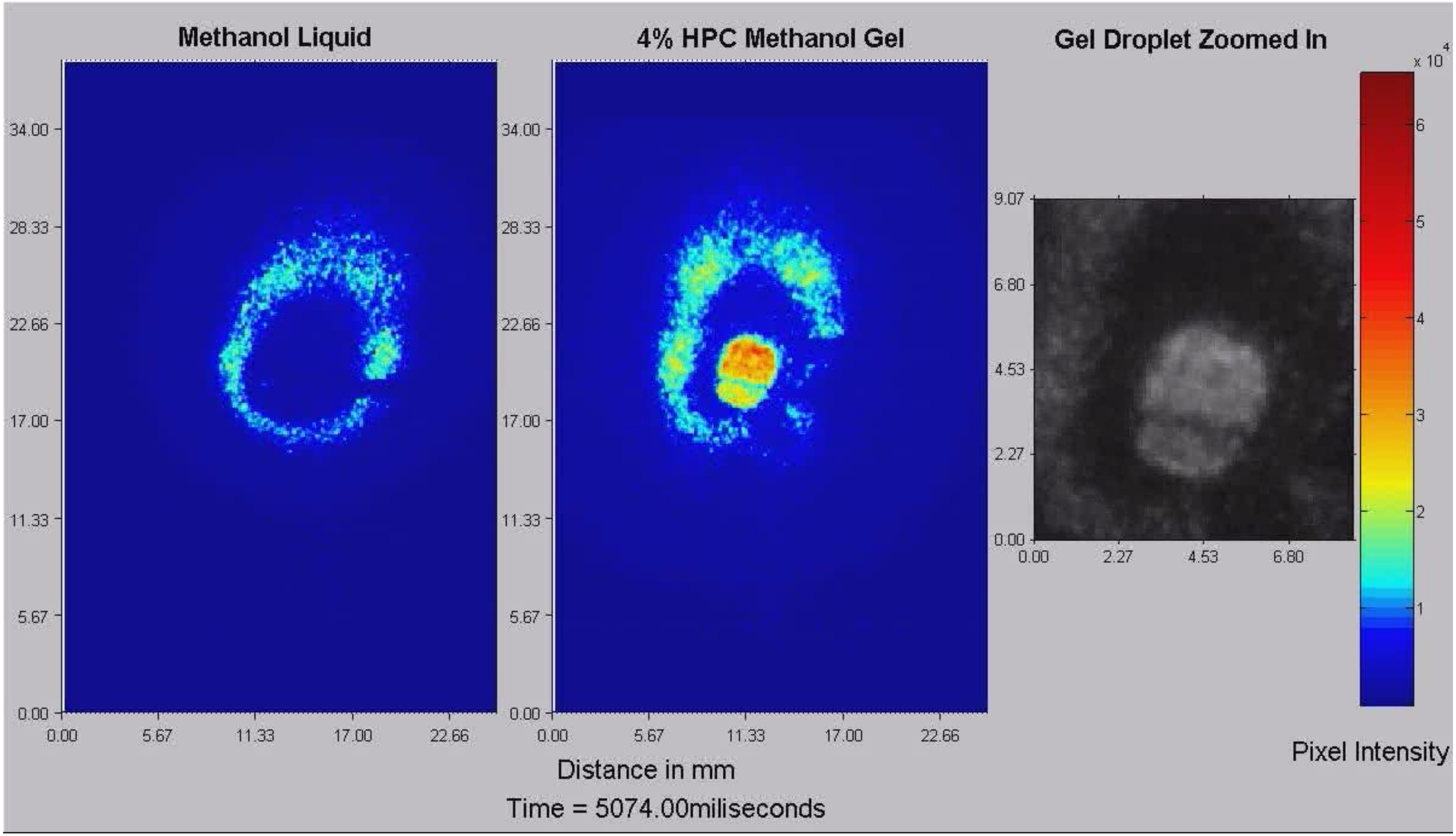
5 kHz OH PLIF of Liquid and Gelled Droplet Combustion



High-Pressure Diagnostic Techniques

- Measurements in high-pressure flames complicated because of the experimental apparatus (windows, etc.) and because of increasing collisional rates (increased quenching, absorption line widths). High-rep-rate PLIF and PIV will be extremely valuable for turbulent flames.
- CARS has been demonstrated in high-pressure flames systems for temperature and concentration. Fs CARS offer the potential for high-rep-rate single-shot measurements in high-pressure systems.
- Dual-resonance techniques like electronic-resonance-enhanced CARS or two-color polarization spectroscopy may help to overcome interferences due to overlapping absorption lines from different species.